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Central Diffractive Processes at the Tevatron, RHIC and LHC*

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Central exclusive production (CEP) processes in high-energy hadron collisions offer a very promising framework for studying both novel aspects of QCD and new physics signals. We report on the results of a theoretical study of the CEP of heavy quarkonia (χ and η) at the Tevatron, RHIC and LHC (see [1] – [3] for details). These processes provide important information on the physics of bound states and can probe the current ideas and methods of QCD, such as effective field theories and lattice QCD.

Recently there has been a renewal of interest in studies of CEP processes in high-energy proton – (anti)proton collisions, [4] – [9]. In particular, such measurements represent a promising way to study the properties of new particles, from exotic hadrons to the Higgs boson (e.g. [1] – [3], [10] – [13]). The CEP of an object X may be written in the form

$$pp(\bar{p}) \to p + X + p(\bar{p}) \ , \tag{1}$$

where + signs are used to denote the presence of large rapidity gaps. An attractive advantage of these reactions is that they provide an especially clean environment in which to measure the nature and quantum numbers (in particular, the spin and parity) of new states, see for instance [14, 15]. An important example is the CEP of the Higgs boson [5, 11, 16], which provides a novel route to study in detail the Higgs sector at the LHC and is complementary to the conventional production mechanisms [16, 17].

CEP processes have been successfully observed at the Tevatron [6, 9] by selecting events with large rapidity gaps separating the centrally produced state from the dissociation products of incoming protons. The CDF measurement [18] of χ_c CEP, for which the experimental signature is especially well-defined, is of particular interest: $p+\bar{p} \to p+\chi_c+\bar{p}$ with *no other particles* in the final state. The CDF result, $d\sigma/dy|_{y=0} = 76 \pm 10(\text{stat}) \pm 10(\text{syst})$ nb in the $\chi_c \to J/\psi + \gamma$ channel with $J/\psi \to \mu^+\mu^-$, was in reasonable agreement with the earlier *pre*diction by Durham group [10] (see also [1]). The broad agreement of the Tevatron results on all CEP processes with the theory lends credence to the Durham theoretical framework and motivates further investigation of new and SM CEP physics at the Tevatron, LHC and RHIC.

The central diffractive production programme at the LHC looks very promising, and the first ALICE results were reported in [8]. However, currently all LHC experiments have insufficient forward coverage, which does not allow a full reconstruction of CEP processes. As emphasized at this meeting by Mike Albrow [6] and Risto Orava [19], the *uninstrumented* rapidity gaps can be covered with sets of simple scintillation counters (FSC = Forward Shower Counters) [20] along the beam pipes. This will allow the selection of $p + X + p$ events, without actually detecting the protons (which could be done with the TOTEM and ALFA detectors). ALICE is installing such counters and they are proposed for CMS [6].

A new area of experimental studies of CEP with *tagged* forward protons is now being explored by the STAR Collaboration at RHIC [7], which has the capability to trigger on and to measure the outgoing forward protons, providing at the same time measurement of the central system with excellent mass resolution. In [3] we pay special attention to exclusive charmonium (χ_{cJ} and η_c) production at RHIC with tagged protons, focusing on the novel and interesting information that the forward proton distributions can provide. We recall that such measurements are unlikely to be possible at other colliders in the near future.

The formalism used to calculate the perturbative quarkonium CEP cross section is explained in detail in [1] – [3]. The expected cross sections and final-state particle distributions (in particular of the outgoing protons) are determined by a non-trivial convolution of the hard amplitude T and the so-called soft survival factors S^2, defining the probability that the rapidity gaps survive soft and semi-hard rescattering effects (see [21] for a review). This is modelled in the SuperCHIC Monte Carlo [22], which allows for an exact generation on an event-by-event basis of the distributions of

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the final-state central particles and outgoing protons, as well as a precise evaluation of the expected acceptances after experimental cuts have been imposed.

$\sqrt{s}$ (TeV)	0.5	1.96	7	10	14
$\frac{\mathrm{d}\sigma}{\mathrm{d}y_{\chi_c}}(pp \to pp(J/\psi + \gamma))$	0.57	0.73	0.89	0.94	1.0
$\frac{\mathrm{d}\sigma(1^+)}{\mathrm{d}\sigma(0^+)}$	0.59	0.61	0.69	0.69	0.71
$\frac{\mathrm{d}\sigma(2^+)}{\mathrm{d}\sigma(0^+)}$	0.21	0.22	0.23	0.23	0.23

TABLE I: Differential cross section (in nb) at $y_\chi = 0$ for χ_{cJ} CEP via the $\chi_{cJ} \to J/\psi\gamma$ decay, summed over the $J = 0, 1, 2$, and cross section ratios of $\chi_{c(1,2)}$ to χ_{c0} production.

As shown in [1, 2], the $\chi_{c(1,2)}$ CEP rates are expected to be heavily suppressed relative to the χ_{c0}, due to the near-exact $J_z = 0$ selection rule that operates for CEP [14, 15], although this suppression may be compensated by the larger $\chi_{c(1,2)} \to J/\psi\gamma$ branching ratios if χ_c CEP is observed via this decay channel (the $\chi_{c1}(\chi_{c2})$ mesons have $30(17)\times$ higher branching ratios respectively). In Table I we therefore show predictions [2] for the $pp \to pp(\chi_c) \to pp(J/\psi\gamma)$ process at RHIC, Tevatron and LHC energies. We note (see also [13]) that a significant fraction of the χ_c events are expected to correspond to the higher spin $\chi_{c(1,2)}$ states. Unfortunately, the $\mathrm{M}(J/\psi + \gamma)$ mass resolution in the CDF measurement [18] did not allow a clear separation of the χ_c states, and so this prediction could not be verified. However, it may be possible to isolate the χ_{c0} CEP contribution via two-body decay channels, with the $\chi_c \to \pi\pi$ decay being a promising example. We recall that such hadronic channels, especially $\pi\pi$, K^+K^- and $p\bar{p}$, are ideally suited for spin-parity analysis of the χ_c states: in particular the fact that the $\chi_{c(1,2)}$ two body branching ratios are in general of the same size or smaller (or even absent for the χ_{c1}) than the χ_{c0} ensures that the $J_z = 0$ selection rule is active, see [1, 10]. In the case of two-body and four-body channels the mass resolution should be much better (of order of a few MeV in the case of STAR [7]) than in the previously observed $\chi_c \to J/\psi\gamma$ channel.

$\sqrt{s}$ (TeV)	1.96	7	10	14
$\frac{\mathrm{d}\sigma}{\mathrm{d}y_{\chi_b}}(pp \to pp(\Upsilon + \gamma))$	0.56	0.70	0.73	0.74
$\frac{\mathrm{d}\sigma(1^+)}{\mathrm{d}\sigma(0^+)}$	0.029	0.032	0.032	0.034
$\frac{\mathrm{d}\sigma(2^+)}{\mathrm{d}\sigma(0^+)}$	0.077	0.081	0.081	0.083

TABLE II: Differential cross section (in pb) at $y_\chi = 0$ for χ_{bJ} CEP via the $\chi_{bJ} \to \Upsilon\gamma$ decay, summed over the $J = 0, 1, 2$, and cross section ratios of $\chi_{b(1,2)}$ to χ_{b0} production.

Table II shows predictions [2] for the central exclusive $pp \to pp(\chi_b) \to pp(\Upsilon\gamma)$ process at Tevatron and LHC energies. While the overall rate is greatly reduced compared to χ_c production, χ_b CEP remains a potential observable at the LHC. We can see that χ_{b1} will give a negligible contribution to the overall rate, while the relative χ_{b2}/χ_{b0} contribution is reduced in comparison to the χ_c case.

Finally, we show in Table III predictions for η_c and η_b CEP at Tevatron and LHC energies [2]. In both cases, as a result of the $J_z^P = 0^+$ selection rule the expected rates are roughly two orders of magnitude smaller than the associated $\chi_{c,b}$ cross sections. We also see that the cross sections are only slowly decreasing with energy. In particular, the χ_c and η_c rates at RHIC are not significantly lower than the Tevatron predictions. This is due to the survival factors (S^2) which increase with decreasing $\sqrt{s}$, and, thus, compensate the decrease in the CEP cross section coming from the smaller gluon densities at RHIC energies [3].

$\sqrt{s}$ (TeV)	1.96	7	10	14
$\frac{\mathrm{d}\sigma}{\mathrm{d}y_\eta}(\eta_c)$	200	200	190	190
$\frac{\mathrm{d}\sigma}{\mathrm{d}y_\eta}(\eta_b)$	0.15	0.14	0.14	0.12

TABLE III: Differential cross section (in pb) at $y_\eta = 0$ for $\eta_{b,c}$ CEP.

In [2, 15], it was shown that the distributions in $p_\perp$ and difference in azimuthal angle ϕ of the outgoing protons depend sensitively on the spin and parity of the centrally produced object. This was studied in detail in [3] where various plots for the expected $\mathrm{d}\sigma/\mathrm{d}\phi$ distributions are given for CEP of $\chi_{c(0,1,2)}$ and η_c states at $\sqrt{s} = 500$ GeV at RHIC. It is also demonstrated that, by applying different cuts to the outgoing proton $p_\perp$, we can probe the underlying theory in a more detailed way. We observe that for low $p_\perp$ the screening corrections do not affect the 'bare' behaviour

too much, while in the case of a relatively large $p_\perp$ the role of absorptive effects becomes quite visible: starting from $\phi = 0$ the absorptive correction increases with ϕ producing the diffractive dip structure in the region of $\phi \sim \pi/2$ for the cases of the χ_{c0} and χ_{c2} and about $\phi \sim 2.3$ for the χ_{c1}. These characteristic 'diffractive dip' structures have the same physical origin as the proton azimuthal distribution patterns first discussed in [23].

A further way to extract spin information about the centrally produced χ state is by measuring the angular distributions of its decays products, in particular, the final state $\mu^+\mu^-$ pair. These spin-dependent angular distributions would also represent an interesting observable, providing complementary information to the tagged proton distributions. A potentially very promising measurement (especially with the STAR detector at RHIC) is χ_{c0} CEP, via two-body (e.g. $\chi_{c0} \to \pi^+\pi^-$, K^+K^-, $p\overline{p}$) or four-body (e.g. $\chi_{c0} \to 2(\pi^+\pi^-)$, $\pi^+\pi^-K^+K^-$) channels, provided the non-resonant QCD backgrounds are sufficiently under control (we recall that the CEP of higher spin $\chi_{c(1,2)}$ states are expected to give negligible contributions via these decay channels). In the case of η_c production, the three-body (e.g. $K\overline{K}\pi$), and four-body (e.g. direct $2(\pi^+\pi^-)$) decay modes appear to be quite promising. The most important uncertainties that are present in our calculation are addressed in [1] – [3].

To conclude, the results of studies in [1] – [3] demonstrate the rich phenomenology that quarkonium CEP processes offer at high-energy colliders. It is also worth mentioning that CEP can help to shed light on the nature of the numerous recently discovered new charmonium-like mesons X,Y,Z [24].

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